APPARATUS AND METHOD FOR CONTROLLING OPTICS PROPAGATION BASED ON A TRANSPARENT METAL STACK

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CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. Non-Provisional Patent Application No. 09/471,035, filed December 23, 1999, entitled "Apparatus and Method for Controlling Optics Propagation Based On a Transparent Metal Stack," which is incorporated herein by reference in its entirety.

This patent application is related to the following applications:

1. "Photonic Bandgap Apparatus and Method for Delaying Photonic Signals," Serial No. 08/584,403, by J. Dowling, M. Scalora, M. Bloemer, M. Tocci, C. Bowden, R. Fork, S. Reinhardt, and R. Flynn, filed on January 11, 1996, now pending and incorporated in its entirety herein by reference;

2. "Photonic Signal Frequency Conversion Using a Photonic Band Gap Structure," Serial No. 09/382,690, by Scalora *et al.*, filed on Aug. 25, 1999, now pending, which is a continuation of International Application PCT/US98/06378, with an international filing date of Apr. 2, 1998, now pending and incorporated in its entirety herein by reference;

3. "Photonic Band Gap Device and Method Using a Periodicity Defect Region to Increase Photonic Signal Delay," Serial No. 09/250,283, by M. Scalora *et al.*, filed on Feb. 16, 1999, now pending and incorporated in its entirety herein by reference;

4. "Photonic Band Gap Device and Method Using a Periodicity Defect Region Doped with a Gain Medium to Increase Photonic Signal Delay," Serial No. 60/134,536, by M. Scalora, filed on May 17, 1999, now pending and incorporated in its entirety herein by reference;

5. "Efficient Non-linear Phase Shifting Using a Photonic Band Gap Structure," Serial No. 60/156,961, by G. D'Aguanno, filed on Sept. 30, 1999, now pending and incorporated in its entirety herein by reference; and

6. "Photonic Signal Reflectivity and Transmissivity Control Using a Photonic Band Gap Structure" S/N 09/471,036, G. D'Aguanno, M. Centini, C. Sibilia, M. Scalora and M. Bloemer, filed on December 23, 1999, and incorporated in its entirety herein by reference.

STATEMENT REGARDING FEDERALLY-SPONSORED RESEARCH AND DEVELOPMENT

This invention was made with Government support under Contract DAAHO1-96-R234 awarded by the U.S. Army Missile Command. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates to transparent metal stacks.

Background Art

[0002] Micro-electro-mechanical-switches (MEMS) have been used in such applications as pressure sensors, accelerometers, and nozzles, and have been proposed for use in radio frequency (RF) telecommunications systems. In particular, a number of different types of MEMS switches have been developed. Petersen, K. "Micromechanical Membrane Switches on Silicon," IBM J. Res. Develop., vol. 23, 1979, pp. 376-385 describes a chemical etching process for fabricating a mechanical switch, which is sensitive to vibrations and has poor insertion loss and isolation. Gretillat et al, "Electrostatic Polysilicon Microrelays Integrated with MOSFETs," in proceedings of Micro Electro Mechanical Systems Workshop, 1994, pp. 97-101 describes a switch for use in an automated testing applications. The switch exhibits large insertion loss and high frequency

capacitive coupling to its polysilicon cantilever arm in its off-state. Yao et al. "A Surface Micromachined Minature Switch for Telecommunications Applications with Signal Frequencies from DC up to 4 GHz" In Tech. Digest, Transducer-95, Stockholm, Sweden, Jun. 25-29, 1995, pp. 384-387 describes a switch for use in RF telecommunications that uses electrostatic actuation to control a silicon dioxide cantilever arm to open and close a signal line, and has an electrical isolation of -50 dB and an insertion loss of 0.1 dB at 4 GHz. These three documents are incorporated in their entireties herein by reference.

[0003] The fields of communications and data processing are currently transitioning from using electrical signals to using optical signals. As a result, there is an increased need for optical devices that perform various tasks in the control of these optical signals. Such devices include tunable filters and optical limiters.

[0004] One method of creating a low distortion, controllable photonic delay is through the use of photonic band gap (PBG) structures. Uniform PBG structures typically comprise a stack of alternating layers of refractive materials of similar thicknesses, such as gallium arsenide and aluminum arsenide, which exhibit photonic band gaps in their transmission spectra. These alternating layers have different indices of refraction and can be deposited by well known deposition techniques onto a substrate.

[0005] By sending a photonic signal of a given frequency (ω) through a uniform PGB device, the discontinuity of the indices of refraction imparts a delay to the photonic signal. These devices slow down the photonic signal as a result of scattering inside the uniform PBG structure. Since the photonic delay is proportional to the square of the number of periods contained in the uniform PBG structure, a device can be constructed that imparts a predetermined delay to a photonic signal. The physical processes involved in the photonic signal delay imparted by a uniform PBG structure are described in detail in Scalora, *et al.*, "Ultrashort pulse propagation at the photonic band edge: large tunable group delay with minimal distortion and loss," Phys. Rev. E Rapid Comm. 54(2),

R1078-R1081 (August 1996), which is incorporated by reference herein in its entirety.

[0006] With the above methodology, an external electric field is applied in order to shift the location of the transmission resonance inside a photonic band gap device to induce changes in the velocity of an externally injected pulse of light. By varying the strength of the applied field, a method by which the index of refraction of the affected material layer can be changed. Changing the refractive index of the layer causes the desired change in the velocity of the incident light beam.

[0007] However, the index of refraction of most ordinary materials can be changed only slightly with the utilization of externally applied electric fields. For example, the index of refraction of GaAs can be changed by approximately one part in 1000 if an ordinary electric field is applied across the 100-nm layer discussed above. That is, a shift in the index of refraction occurs from 3.4 to 3.401. While this shift can be considered meaningful, experimentally observable, and useful for some applications like an optical delay line, this shift is too small and impractical for many other applications of interest. As an example, this change in index of refraction from 3.4 to 3.401 can shift the transmission resonance in a photonic band gap structure by approximately 0.5 nm. While this shift may be adequate for control of the velocity of an optical pulse, it is completely inadequate for device applications such as optical limiters and tunable filters wherein device requirements can be very demanding. For example, an optical limiter must stop a coherent signal regardless of its wavelength. This means it must distinguish between low intensity light levels, such as those of ambient light, and a high intensity coherent light, such as a laser beam. In addition, the device must be able to discriminate between different colors of the incident light, coherent or not, over the entire visible range. That is, it must have a dynamic range approximately 1000 times greater than the shift discussed in our previous patent application and incorporated by reference herein in its entirety, i.e., from 0.5 nm to approximately 500 nm or more.

[0008] Hence, there is a need for a device and method to change the index of refraction by greater than a factor of 2 in a number of readily available materials.

BRIEF SUMMARY OF THE INVENTION

[0009] The present invention generally relates to a device and method of optics propagation and signal control integrated with micro-electro-mechanical-switches (MEMS). In particular, the present invention relates to modifying optical transmission properties of a transparent, multilayer metal stack by mechanically varying the thickness of an air gap between layers in the stack. This is accomplished with the novel approach of utilizing MEMS coupled with the stack to change the index of refraction in a given layer of the transparent multilayer metal stack.

[0010] According to one embodiment of the present invention, this is accomplished by developing a hybrid combination of transparent multilayer stacks and MEMS, wherein an air gap is used as one of the dielectric layers. The air gap thickness can be controlled by the MEMS device thereby enabling much greater control of the index of refraction.

[0011] Further features and advantages of the present invention, as well as the structure and operation of various embodiments of the present invention, are described in detail below with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS/FIGURES

[0012] The present invention is described with reference to the accompanying drawings. In the drawings, like reference numbers indicate identical or functionally similar elements.

[0013] FIG. 1A is a representation of a transparent metal stack.

[0014] FIG. 1B is a chart of the transmission function of the transparent metal stack of FIG. 1A.

[0015] FIG. 2A is a representation of a transparent metal stack of the present invention including the novel air gap as one layer and in the open position.

[0016] FIG. 2B is a representation of a transparent metal stack of the present invention including the novel air gap as one layer and in the closed position.

[0017] FIG. 3 is a chart of the transmission function (depicted as a solid curved line) of the device arrangement of FIG. 2A, and a chart of the transmission function (depicted as a dashed line) of the device arrangement of FIG. 2B.

[0018] FIG. 4 is a series of transmission functions for an embodiment of an air gap device according to the present invention, each of the transmission functions corresponding to a predetermined air gap width in the air gap device.

[0019] FIG. 5 is a diagram of an actual micro-electro-mechanical optical switch constructed in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0020] An example of a transparent metal stack 5 is shown in FIG. 1A, and the transmission function 20 thereof is shown in FIG. 1B. Stack 5 consists of alternating layers of silver and any material whose initial refractive index is approximately 1.37, with thickness 140 nm. The corresponding transmission function 20 is represented as a solid-line of FIG. 1B: the structure is transparent to wavelengths that fall in the visible range.

[0021] An optical path is a quantity that is defined in terms of the index of refraction and the physical thickness of any material. More precisely, the optical path D is the product of the index of refraction and the physical thickness (or absolute thickness) of the material, i.e., D=nL. For example, the index of refraction of GaAs is n=3.4 at a wavelength λ =1.5 microns. The optical path of a 100-nm thick GaAs layer (L=100 nm) is D=340 nm at a wavelength of 1.5 microns. Therefore changing the index of refraction in a given layer is equivalent to modifying the optical path of that layer.

[0022] Assuming that one can apply an external excitation to the dielectric layers such that the effective path of each layer now become approximately 50 nm, then the transmission function changes. The changed transmission function is depicted by the dashed line in FIG. 1B. The device is now opaque to ALL radiation, from ultraviolet to microwave fields. This kind of operation can best be described as optical limiting. That is, the device can react to a perceived threat, which might be in the form of a laser or microwave field, by completely shutting itself down and not allowing the propagation of any radiation. Unfortunately it is difficult to find materials that respond in the manner described above, by changing their index of refraction by a factor of 2 via the application of a magnetic field, for example.

[0023] Referring again to FIG. 1A, metal stack 5 comprising alternating layers of a metal 10, such as silver, and any dielectric material 15 whose initial refractive index is approximately 1.37, with thickness 140 nm. It is understood that the measurements herein are used for illustration and other thickness' can be used if in the appropriate proportion. The transmission function waveform 20 is shown in FIG. 1B, wherein it is shown that the structure is transparent to wavelengths that fall in the visible range. The Y-Axis 25 depicts the transmission level and the X-axis 30 depicts the wavelength in nanometers.

[0024] Micro-electro-mechanical-switches, or MEMS, can be a potential alternative to nonlinear optical devices. In nonlinear optics, as described in the patent applications incorporated above by reference, a high intensity beam in the form of an electric field, a magnetic field, or both, is used in order to change the physical properties of an ordinary dielectric material. By physical properties, we generally mean the index of refraction of the material, which could be a type of glass for example, or a semiconductor like Gallium Arsenide (GaAs).

[0025] In the present application we describe a device based on a hybrid combination of transparent metal multilayer stacks and MEMS that will perform approximately as outlined above. The device limits the transmission of high intensity light and will have a dynamic range on the order of 100 nm or more.

[0026] An example device is described below with reference to FIGs. 2A and 2B. With reference to FIG. 2A, a transparent metal stack 200 includes a left stack region 200a and a right stack region 200b separated by a dielectric air gap layer 205. Air has a refractive index equal to 1. The important parameter here is the optical path of the air gap, which can be made to be equivalent to the optical path of the other dielectric layers by controlling its thickness 210.

[0027] To this end, a micro-electro-mechanical-switch assembly 212 controls the thickness 210 of air gap layer 205 by displacing left and right stack regions 200a and 200b toward or away from each other. MEMS assembly 212 includes an actuator unit 214 coupled with a left arm 216a and a right arm 216b. Left and right arms 216a and 216b are in respective contact with left and right stack regions 200a and 200b. Actuator unit 214 displaces arms 216a and 216b, and as a result, left and right stack regions 200a and 200b, toward and away from each other, in response to a control signal 218 applied to actuator unit 214, to thereby control thickness 210 of air gap layer 205.

[0028] FIG. 2A represents a device arrangement wherein MEMS assembly 212 has established an air gap thickness 210. On the other hand, FIG. 2B represents a device arrangement wherein MEMS assembly 212 has established an air gap thickness of approximately zero by bringing left and right stack regions 200a and 200b together from their separated positions in FIG. 2A.

[0029] The results below are of a mathematical model that describes light propagation inside the multilayer stack. It is assumed the stack comprises the following arrangement of materials:

Glass Substrate

Ag	20.00 nm
MgF_2	150.00
Ag	25.00
MgF_2	149.80
Ag	60.00

MgF2 25.00

Air Layer 205 of variable width 210:

MgF2 25.00 nm
Ag 60.00
MgF2 150.00
Ag 25.00
MgF2 150.00
Ag 20.00
Glass Substrate

[0030] The respective transmission functions of the example device corresponding to the arrangements of FIGs. 2A and 2B are schematically represented in FIG. 3 by a solid line curve (for FIG. 2A) and a dashed line curve (for FIG. 2B), wherein the transmission percentage light propagation 315 is represented by the Y-axis and the wavelength is represented by the X-axis 320.

[0031] When the width of the air gap 210 depicted in FIG. 2A is approximately 150 nm, the device allows nearly 30% of the incident light to be transmitted in the visible range as shown at transmission peak 300 of FIG. 3. All other radiation over the entire spectrum is reflected or slightly absorbed as represented by a transmission low level 305 of FIG. 3. On the other hand, if the air gap width is reduced to approximately zero, as shown at 220 in FIG. 2B, we have a continuous layer of MgF2 50 nm wide in the center 225 of the structure. From the optical point of view, this layer spoils the resonance tunneling phenomenon which otherwise allows the propagation of the visible wavelengths. This absence of propagation is illustrated as the dashed line 310 of FIG. 3. If the thickness of this central layer falls below a certain value, it ceases to be effective, and could in principle be removed. However, when the stacks are separated, the thin MgF2 layers serve as protective layers for the outer silver layer. Therefore, when the

two sides are touching or nearly touching, as shown in FIG. 2B, the calculation shows that the transmission through the stack is reduced to approximately 0.3%, or approximately a factor of 100 less compared to the "open" state, as shown in FIG. 2A.

[0032] Using this approach, therefore, it becomes possible to replace nonlinear optical interactions with ordinary oscillations or motions of mechanical systems. A 60% change in the optical path of the air gap layer (or any other layer within the structure as long as it is possible to change its optical path by a large amount) allows a drastic change of the transmissive properties of the device, as shown in FIG. 3. For example, and not by way of limitation, the device depicted in FIG. 2A and 2B can be an optical limiter, which allows light to be transmitted in the open position, and which rejects most of the light in the closed position. An example dielectric material that was used is MgF2. However, other dielectric materials, such as Silicon Nitride, or Titanium Dioxide can be used.

[0033] Operation as a tunable filter is slightly different, with theoretical results illustrated in FIG. 4, wherein the percentage light propagation is the Y-axis 405 and the air gap thickness is the X-axis 460. For illustration, Silicon Nitride has been used in the following device layer configuration:

Glass substrate

SI3N4	65.00 (nm)
AG	10.00
SI3N4	98.00
AG	20.00
SI3N4	94.00
AG	30.00

AIR layer having exemplary widths 470; 490; 510; 530; and 550 nm

AG	30.00
SI3N4	94.00
AG	20.00

SI3N4	98.00
AG	10.00
SI3N4	65.00
Glass substrate	

[0034] The tunability is graphically depicted in FIG. 4 wherein the X-axis 460 is the air gap thickness in nm and the Y-axis 405 is the percentage light propagation. The design is similar to the apparatus of FIGs. 2A and 2B, except that in this embodiment the air gap thickness varies from 470 to 550 nm. In FIG. 4, transmission profiles 410, 420, 430, 440 and 450 respectively correspond to exemplary air gap thicknesses 470nm, 490nm, 510nm, 530nm and 550nm. The graphical illustrations are by way of example only and it is understood that any variations of the air gap thickness can be used depending on the characteristics of the tunable filter desired. It is noted that it is possible to incorporate two or more air gaps in the device, which allows for greater tunability control.

[0035] A micro-electro-mechanical optical switch 500 constructed in accordance with the principles of the present invention is depicted in FIG. 5. Switch 500 includes an upper silicon section 502a, and a substantially identical, opposing lower silicon section 502b, bonded together to form a cavity 504 between the upper and lower sections. Upper section 502a includes a pair of substrates 504a and 506a spaced apart from one another in a lateral direction L, and a transparently thin, laterally extending, flexible membrane 508a between the spaced substrates. Similarly, lower section 502b includes a pair of spaced substrates 504b and 506b and a transparently thin, laterally extending, membrane 508b between the spaced substrates. Upper and lower silicon sections 502a and 502b are bonded together at seems 510. Upper and lower silicon sections 502a and 502b can be fabricated using a bulk micro-machining technique. Also, silicon sections 502a and 502b can be made of suitable materials other than silicon.

[0036] A pair of PBG multilayer stack regions 512a and 512b, constructed in accordance with the present invention to exhibit desired optical properties, are deposited on respective inner surfaces of membranes 508a and 508b to thereby oppose one another within cavity 504. A first pair of laterally spaced actuators 514a and a second pair of laterally spaced actuators 514b opposing the first pair are respectively embedded in the outer surfaces of the upper and lower sections 502a and 502b. Actuator pairs 514a and 514b are respectively positioned at edge portions of flexible membranes 508a and 508b and control a separation or width 520 between opposing stack regions 512a and 512b by displacing the respective deformable membranes in a vertical direction V. Each actuator pair 514a/514b advantageously maintains an even or level orientation of the respective membrane 508a/508b, and thus stack region 512a/512b, while displacing the membrane in direction V because of the laterally spaced configuration of each actuator pair. Accordingly, the optical transmission of a light beam 522, directed at stack region 512b as depicted in FIG. 5, through optical switch 500 is controlled by varying separation 520 using actuator pairs 514a and/or 514b, as described above.

[0037] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. It will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined in the appended claims. Thus, the breadth and scope of the present invention should not be limited by any of the above described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.